Anticipating the flash floods in dry valleys (northern France) by cellular automata modelling

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Abstract

This paper presents an application of a cellular automaton based runoff model (RUICELLS) to a series of small and dry valleys in the Seine-Maritime department, northern France, to assess their susceptibility to flash floods. These muddy floods shortly follow high rainfall (50-100 mm in less than 6 hours) and occur in very small (< 20 km^2) basins. A surge generally rushes down through the main valley just a few minutes after rains have peaked. Previous events (n = 69, in the period 1983-2005) have occasionally threatened human lives and have caused significant damage to property and infrastructure. Nonetheless given the variation among the valleys and the infrequency of events, these floods have not been numerous enough, to permit a statistical analysis. Instead, we numerically simulate the possible future flash floods using RUICELLS, a cellular automaton model driven by a set of three deterministic hydrological rules. Simulations have been conducted for 148 basins, each subject to 16 different rainfall scenarios (i.e. 2368 simulations in total), to estimate the peak-flow discharges (Q), the specific peak-flows (Qs) and the lag times (T) of the flash floods, and to identify the critical rainfall intensities that would trigger warnings and increased vigilance. Our simulations indicate that the number of basins susceptible to flash flooding greatly increases with higher rainfall intensity, the distribution of sensitive crops (sugar beet, corn, maize, flax) and the basin morphology. Several small basins could also induce by convergence a bigger flood in the downstream humid valley. The location of the highest simulated discharges aligns with observed events, which provides an evaluation of the modelling performance and the credibility of the results.

Key words: *flash flood; dry valleys; susceptibility assessment; northern France.*

1. Introduction

Flash floods in northern France (Masson, 1987; Devaud, 1995; Merle, 2001; Arnaud-Fassetta *et al*, 2012) induce serious risk conditions on populated outlets, especially in the Seine-Maritime department (Delahaye *et al.,* 2001; Douvinet, 2008, 2014; Douvinet *et al.,* 2013). These hazards are generated shortly after rains ranging from 50 to 100 mm in less than 6 hours and occur in small dry valleys (< 20km^2). Such flash flood present distinct features: a violent onset, a rapid rising time and a surge rushing down just a few minutes after rainfall peaked. Previous floods have occasionally threatened human lives (11 persons died over the period 1983-2005 in this department), and caused significant damage to property and infrastructure (ranging from 0.05 to 14 million Euro for the 1997, June 16th event). The hydrological and geomorphological characteristics are quite similar to others occurring in other sedimentary areas, in western France (Auzet *et al.,* 1995) or in Flanders (Evrard *et al.,* 2007) for example, but are notably different to French Mediterranean floods. The latter occur in basins with higher slope-gradients, larger basin area (ranging from 50 to 300 km^2) and are typically associated with higher rainfall intensities (Antoine *et al*., 2001; Collier and Fox, 2003; Reid, 2004; Barrera *et al.,* 2006; Ruin *et al.,* 2007; Calvet and Lemartinel, 2009; Ortega and Heydt, 2009; Gaume et al., 2009; Morin *et al.,* 2009; Marchi *et al*., 2010).

Predicting the time of occurrence and the intensity of northern flash floods remains difficult at larger scales for several reasons: measurements and field-based experimentations are rarely conducted in small dry valleys; these phenomena are insufficiently documented and remain difficult to monitor as they produce destructive effects to measuring devices; the rarity of events and the long recurrence intervals hamper statistical analysis and calibration of models (Ferraris *et al.,* 2002); the short distances between source areas (runoff production) and risk zones (i.e. settlements) frequently surprises inhabitants in a few minutes; changes in velocity, roughness and water height introduce uncertainties in the estimation of peaks discharge (Gaume *et al.,* 2009; Douvinet and Delahaye, 2010) and strongly hamper the classical hydrological approaches (Lumbro and Gaume, 2012).

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Because of the statistical models' reliance on extensive inventories of location-specific past events, they are less transferable between different areas. Furthermore, they only implicitly represent the impacts of processes, rather than the processes themselves (Kappes *et al.,* 2012). Conversely, the physically-based models, including cellular automaton (CA) models, consider common physical characteristics of salient processes, and are more readily transferable between sites (Coulthard and Van De Wiel, 2006; Ménard and Marceau, 2006; Van de Wiel *et al.,* 2007). Consequently, we propose applying a CA model, i.e. RUICELLS (Delahaye *et al.,* 2001; Douvinet *et al.,* 2013), to anticipate the spatial occurrence and areas at risk. The RUICELLS model requires fewer parameters than most other physically-based models, as distributed (or semi-distributed) hydrological models or soil erosion models (SEMs). Although a few similarities exist between these models (e.g., SEMs need to determine surface runoff before they can calculate soil erosion), the main difficulties is the greater number of environmental factors required (Nearing *et al.,* 2005).

By means of a combination of environmental parameters, chosen on the basis of previous experiences, three variables (peak flow, specific flow and lag-time) were calculated for 16 rainfall scenarios on 148 basins (2386 simulations in total). The methodology applied here simplifies rainfall inputs to 16 rainfall scenarios. The reason for this is twofold. First, even though the recent efforts in meteorological observations provide relevant details on timing and location of convective storms (Collier, 2007), the existing models (e.g. AROME or PANTHERE) do not yet predict rainfall intensities either with sufficient precision at fine scales (< 10km^2) or with sufficient advance warning (1h). Second, this simplified rainfall approach allows us to control the end-to-end simulation process (Fonstad, 2006), measuring the transformation of input to output data, testing the sensitivity of basins to initial conditions and defining their reactivity to different rainfalls with which we cannot experiment in reality.

2. Study sites

An earlier study of 189 basins affected by flash floods over the period 1983-2005 in northern France (Douvinet, 2008) allowed the identification of a certain number of properties that make basins susceptible to flash floods. Extrapolation of such criteria over the department of Seine-Maritime allows the identification of 148 basins with similar features (**fig. 1**). Firstly, all these basins are inhabited at their outlet, and thus potentially exposed to flash flooding hazards. Consequently, the simulations may improve knowledge on risk and critical rains, which can be

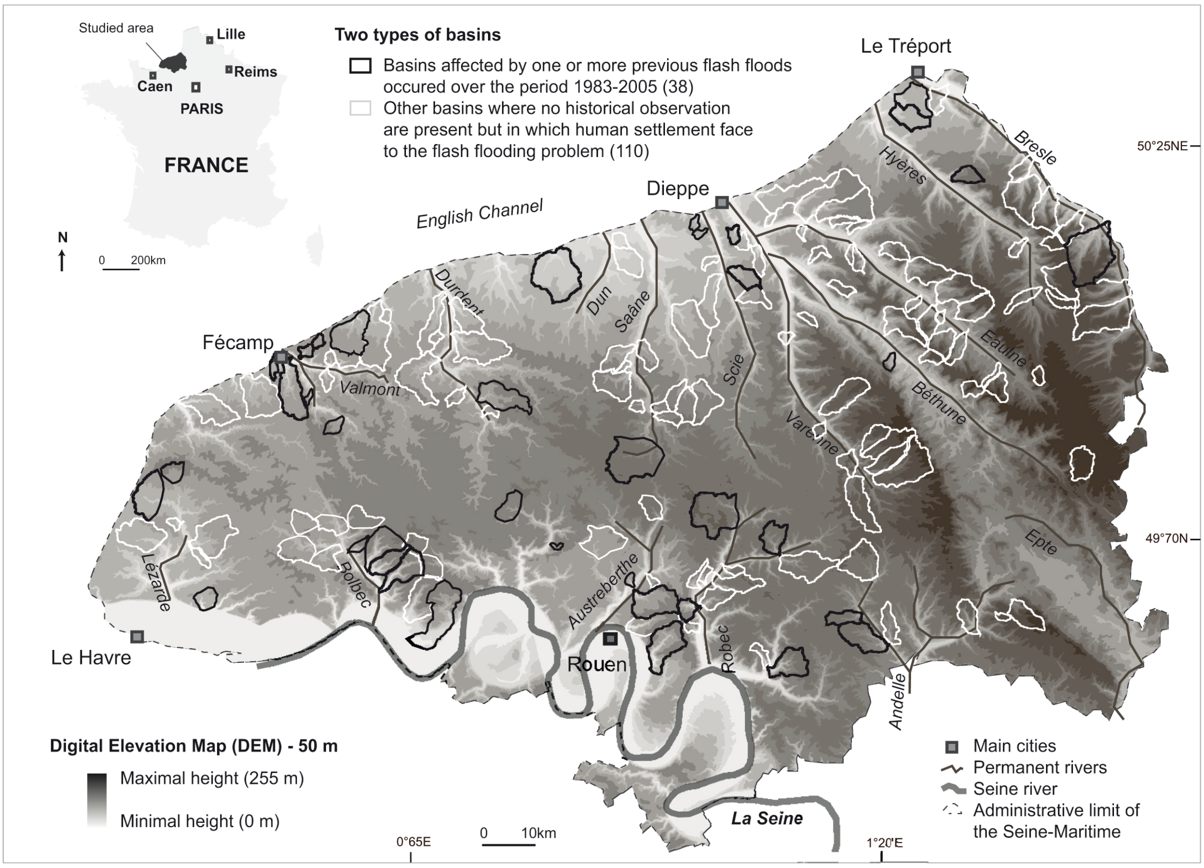

Fig. 1. Schematic topographic and hydrographic conditions in Seine-Maritime (northern France) and location of the 148 studied basins including the 38 basins affected by previous flash floods (1983-2005).

used to trigger increased vigilance or alert warnings as soon as possible. Secondly, the basins are small in size (< 20km^2), including 67 very small basins (< 5km^2), 54 basins of medium size (from 5 to 9 km^2) and 30 "bigger" basins (from 9 to 20km^2). They also include the steepest departmental slopes (ranging from 2 to 15%) and long profiles (up to 3%) and are always connected to major humid valleys in short distances (< 3km) creating an order gap in the Strahler (1952) network ordination (Douvinet *et al*., 2013). This explains why hydrological responses (<2h) and meteorological conditions at fine scale (< 1km) are crucial, but also why anticipating events remains difficult (Douvinet *et al.,* 2013). Thirdly, the average percentage of grass, forests and/or cultivated areas at basin scale varies strongly (**tab. 1**). The spatial interactions between the runoff production (from cultivated areas) and water flow pathways (influenced by the morphology) are more important than the overall land use percentages. As a basic example, the basin of St-Martin-de-Boscherville (with only 22% of cultivated areas) induced the most dramatic event (4 victims on June 16th, 1997) over the period 1983-2005. Fourthly, all the basins have common morphostructural features, since they all belong to the Parisian Basin. The landscapes consist of successive sub-horizontal to slightly undulating plates (Mathieu *et al.,* 1997) incised by dry valleys, which are inherited from the Quaternary periglacial periods (Lahousse *et al.,* 2003; Larue, 2005). Finally the dominant soils (i.e luvisols) are characterized by small rates of organic matter (< 2%) and clay (< 15%), but high contents of silt (> 70%). This soil component renders the soils highly vulnerable to erosion in spring and summer. The surface degradation under raindrop impact induces a strong reduction of infiltration capacities, and the progressive disappearance of soil roughness concentrates runoff water. This explains why the soil erosion is extensively studied in this region, where the land-use dynamics and agricultural practices increase runoff production (Souchère *et al.,* 2005).

Name of basins (25)	Date of events [A]	Size (km^2)	Relief (m)	Average height (m)	Slopes STTD [B]	Gravelius index [C]	Forests (%)	Grass (%)	Cultivated (%)	Urban (%)
Canteleu	2003/06/24	0.74	113.1	75.9	33.04	1.18	69.2	4.2	4.2	22.4
Folletière	1998/06/06	0.76	93.4	117.2	24.63	1.14	20.2	5.3	66.2	8.3
Blanchisserie	2000/05/09	1.11	97.4	99.0	27.24	1.40	4.1	30.5	56.2	9.2
Hautot-sur-Mer	2005/05/28	1.14	95.4	71.2	24.23	1.23	7.8	53.1	14.1	25.0
Fernague *	2001/08/02	1.62	107.2	113.5	26.42	1.34	32.4	10.3	41.2	16.1
St-Léonard *	2000/05/10	1.81	73.1	88.4	13.36	1.10	0.3	4.9	65.1	29.7
Quatre Vaux *	1998/05/13	2.89	76.2	117.9	14.30	1.17	9.4	0.2	88.1	2.3
St-Paer *	1997/06/16	3.50	88.1	102.4	15.79	1.23	9.2	31.4	51.6	7.8
Betteville	1998/06/06	3.72	106.2	99.1	21.39	1.14	17.7	15.3	63.6	3.4
Houlme	1988/05/07	4.55	111.3	115.9	24.78	1.09	31.7	18.1	30.1	20.1
Gomare	1998/06/06	4.86	122.1	130.2	29.93	1.21	25.7	15.1	50.3	8.9
Pissotière	1993/06/09	5.05	100.2	87.2	17.63	1.06	15.1	14.2	51.5	19.2
Fresnaye	1992/06/09	5.66	127.2	114.1	28.59	1.31	38.8	18.2	31.9	11.1
Blanville	1997/08/06	6.80	77.2	155.6	13.88	1.34	3.2	10.4	79.3	7.1
Fontaines	1997/06/16	9.29	137.2	109.6	27.90	1.33	37.9	10.7	47.3	4.1
Auffay	1998/06/06	10.15	64.4	148.0	13.23	1.25	21.8	14.6	57.4	6.2
Darnétal	1995/08/06	10.29	133.4	138.9	28.79	1.22	35.2	6.7	33.5	24.6
Puits-Maillé	1998/05/13	10.62	139.2	118.2	32.33	1.30	26.4	5.6	59.5	8.5
Baret	1998/06/06	11.14	60.3	107.7	11.04	1.16	8.1	21.1	64.8	6.0
Ry	1997/08/06	11.57	97.6	146.7	19.09	1.21	10.1	12.7	64.1	13.1
Fontaine-Murée	1993/06/09	11.96	158.6	156.5	44.81	1.29	26.5	27.2	44.1	2.2
Val aux Clercs	1998/05/13	13.60	110.9	100.7	21.36	1.29	6.6	20.2	61.7	11.5
St-Martin **** [(D)]	1997/06/16	14.21	132.5	111.1	25.98	1.19	44.6	17.4	21.8	16.2
Villers-Ecalles	1994/07/19	14.48	106.1	113.3	19.42	1.24	23.6	9.3	52.8	14.3
Oudalle	1993/06/09	18.59	129.3	104.5	25.31	1.57	14.5	7.1	72.1	6.3
Minimum	-	0.74	60.3	71.2	11.04	1.09	0.3	0.2	4.2	2.3
Maximum	-	18.59	158.6	156.5	44.81	1.57	69.2	53.1	88.1	29.7

A This information has been extracted from the files related to the French recognition of the "state of natural disaster" (CATNAT database).
B Standard Threshold Deviation (STTD) for the slope systems (automatically calculated by ESRI ®Arc Gis 9.8).
C This Gravelius index represents the fraction between the perimeter of one basin and the perimeter of a circle having the same surface.
D The number of asterics indicates the number of victimes recorded after the flash flood events (from Douvinet, 2008).

Tab. 1. Physiographic and land use characteristics for 25 (of 38) basins (classified by increasing size), on which one flash flood has occurred over the period 1983-2005 (from Douvinet, 2008).

3. Material and methods

3.1. CA background for hydrological modelling

Cellular automaton (CA) models increasingly contribute to hydrological or geomorphological studies over the last decade (e.g. Ménard and Marceau, 2006; Coulthard *et al.,* 2007; Van de Wiel *et al.,* 2007, 2011). In these dynamic models, the global properties arise from the local and spatial interactions of cellular entities (Wolfram, 2002; Fonstad, 2006). A lattice on which each cell possesses its own state characterizes these models. The time is discrete and the state of cells updated through the application of a set of predefined rules (Phipps and Langlois, 1997). These rules, either expert-based, deterministic or probabilistic, dictate how the cells interact with their neighbors. The CA modelling approach is decades old, introduced by Von Neumann in 1951 (Gardner, 1970), made famous by Conway's *Game of Life* (1970) and has supported an array of advances in many fields since the 1980's in physics, mathematics, chemistry, ecology, and since the mid-1990's also in geomorphology (Douvinet *et al*., 2013). For example, the CA models have been used to study aeolian ripples (Anderson, 1990), forest-fires (Clarke *et al.,* 1994), debris-flows (Di Gregorio *et al.,* 1998), debris-laden floods (Bursik *et al.,* 2003), lava dynamics (Avolio *et al.,* 2006), channel meandering (Coulthard and Van de Wiel, 2006), the evolution of coasts (Dearing *et al.,* 2005) and the response modelling of river systems (Van de Wiel *et al*., 2011) among others.

Murray and Paola (1994)'s braided river model was the first CA including hydrological and geomorphological processes, although their representations of river processes did not include explicit time and real physical scaling (Parsons and Fonstad, 2007). Thomas and Nicholas (2002) extended the Murray-Paola model to simulate more realistic flow dynamics in braided river systems. Other water flow models have been developed, e.g to simulate the growth of small rills in response to hillslope erosion (Favis-Mortlock, 1998), to measure soil erosion at microscopic scales in SoDa (Valette *et al.,* 2006) or to simulate basin responses using a wave approximation for in- channel flows (De Roo *et al.* 1996). Coulthard *et al.* (2007) and Van de Wiel *et al.* (2007) recently introduce a gradually-varied CA for catchment evolution modelling that includes sediment transport dynamics. A more recent version (Coulthard *et al.,* 2013) includes unsteady catchment hydrology. Although all these models differ considerably in their aims and implementation details, they share a common conceptual design in which a link is established between topographic variables, such as the elevation and its derivative, and hydraulic variables, such as water fluxes and flow velocity. The rules of each CA model describe the precise nature of that link.

CA models can also be linked with smoothed particle approaches (e.g. Drogoul, 1993) to better assess generic dynamics or hydrological fluxes. In recent years, agent-based modelling (ABM) has been tested in hydrology and geomorphology after first initiatives in ecology, sociology or human geography. These models may provide alternative approach to CA modelling. For example, CATCHSCAPE allow simulating the hydrological system with its distributed water balance or to irrigate schemes management, crop and vegetation dynamics (Bécu et al., 2003). ABMs can be used in alluvial plains where processes between independent interacting entities behave according to the local environment (Teles *et al.,* 1998). But the agent-based modelling applications remain less used than CA in geomorphology as the attention is more drawn on interactions between human or autonomous entities, more than on physic components, and because CA conveniently have an inherent spatial structure.

Another alternative modelling approach is distributed modelling, improving the lumped models that only predict discharges at outlets. However, even though distributed hydrological models, also based on the Digital Elevation Maps (Moussa and Bocquillon, 1996; Cudennec *et al.,* 2002; Kirkby *et al*., 2005), are supposed to be spatially explicit over the entire basin, they are usually validated and calibrated at the outlet. None of them allow for the estimation of potential surface flow concentration in all parts of a basin since the drainage limit-divide (Douvinet *et al*., 2013). Previous studies are also focused on the relation between the global catchment morphology and its hydrological response measured at the final outlet. These studies underlined the difficulties encountered when linking local responses (sub-basins or hillslopes) to this global behaviour and this aim has been one of the main issues for geomorphologists since the 1970s (Veltri *et al.,* 1996; Rodriguez-Iturbe and Rinaldo, 1997; Schmidt *et al.,* 1998). A few studies have successfully shown that the network organization plays a key role on hydrological functionality (Dietrich *et al.,* 1993; Vogt *et al.,* 2003). The CA RUICELL partially overcomes such difficulties and also implicitly captures the channel network structure and its influence on flood through scales.

3.2. The RUICELLS' spatial structure and conceptual design

Similar to other hydrological or geomorphological CA models, the RUICELLS model establishes a link between topographic variables and hydraulic variables. In this sub-section, we focus on RUICELLS' spatial structure and conceptual design, more than on all the mathematical relations underlying the process representation that is too cumbersome and too space consuming. A full description of the RUICELLS model, including its mathematical structure, can be found in Delahaye *et al*. (2001), Langlois and Delahaye (2002) and Douvinet *et al*. (2013).

The diversity of the topography and the variety of the mechanisms involved precludes a global modelling of the runoff process and it requires a sharp division of the concerned area into homogeneous and interconnected cells. In RUICELLS, the original CA concept is generalized to incorporate the variety of the topographical conditions: elementary surfaces on hillslopes, linear portions of thalwegs, and local depressions. The spatial dimensions of cells thus are 0, 1 or 2 (point, line or surface). Moreover, the connections of the automata are directed only by the neighbourhood topology of cells, but also by morphological links organizing the space: the links of discharge between the cells and the links of overflow between the sub-basins.

The spatial domain is discretized as a Triangular Irregular Network (TIN), based on the Digital Elevation Map (DEM) according to square grid **(fig 2a)**. Two techniques are available to create a lattice: a function obtained by the calculation of differences between neighbouring cells (Laurent *et al*., 1998), or the meshing in finite elements which gives a continuous interpolation between points of the DEM. We have chosen the latter, which gives for each point its elevation and its vector normal to the surface, allowing the calculation of every measure of size related with the local shape of the terrain (slope angle, exposition, run-off vector, and then surfaces, volumes, flow). Consequently we have divided each square cell into two triangles, choosing one of the diagonals to define the triangle **(fig. 2c)**. This choice is relevant since the diagonals do not cross at the same height. To improve the outflow, the chosen diagonal is those with the minimum height at the crossing point, with no risk of obstructing a stream channel. The steepest downward link determines the flow direction, analogues to D1 and D8 algorithms for other square lattices (O'Callaghan and Mark, 1984; Tarboton, 1997). This TIN structure, because of its linear applications, offers the simplest finite elements model and a substantial gain if we want to operate on a PC with a very large amount of cells. Importantly this spatial structure overcomes one of the main disadvantages of many CA models, namely that flow directions are constrained to 45-degree intervals at any cell.

In order to access the geometric information, the topological graph applied on the TIN structure is composed of three main features: node, arc or triangle, inducing the following relational tables **(fig. 2d)**. The arcs play a major role: each arc is connected to two nodes and two triangles and a morphological attribute may be given to it by the relative heights of the former and the relative slope angles of the latter. Comparing heights of two nodes, we can see if the connecting arc is downhill, uphill or flat. As for the triangles, two of them (side by side) may be also, individually, downhill, uphill or flat. An arc whose final node is lower than the initial one is downhill but if its two neighboring triangles are downhill towards it, it equals a downhill thalweg **(fig. 2d)**. The typology gives $3^3=27$ theoretical possibilities. After eliminating some rare and specific situations we have kept several attributes for the arcs. The "external limit" has been introduced to handle with the limits of the studied area. The "flat" is attributed to the limit between two flat triangles. It must be stressed that these attributes are purely local: if an arc equals a downhill thalweg, there is no continuity for the downstream arcs. Yet its knowledge is important to determine the runoff process, which is linear along this arc, while if the arc attribute is left slope, the runoff is a sheet-flow and its direction transversal.

For the runoff graph, it is not easy to feature the global network of the thalwegs due to the lack of continuity for the local morphology **(fig. 2e)**. When the thalweg becomes wider, it is formed by a certain amount of triangles in which there is a sheet-flow transversal to the arcs. The local attributes of arcs are no longer sufficient to shape the network. All the links between the elements (poles, arcs, triangles) of the topological graph must be taken into account. The resulting graph is similar to one oriented dual topological graph, but is in fact more complex, as the dual graph connects only triangles, whereas here, it connects poles, arcs and triangles. A drop of water laid on a triangle may flow towards the neighbouring triangle if the connected arc is a left slope, but may flow in the arc itself if it is a downhill thalweg. The drop may flow, afterwards, towards a triangle or another arc, or may be stopped in a pole if it is a depression. A triangle can be connected upstream to three neighbouring triangles at the most, but it may also receive water from one or more thalwegs arriving by one or more of its vertices. It may be connected also downstream to one or two neighbouring triangles. In this latter case, transition factors must be calculated to define, on each side of the line of greater slope angle, the proportion of the flow towards each of the two downstream triangles **(fig. 2f)**.

In certain conditions additional complications may arise. For example, channel streams in dry valleys are mostly ephemeral, using an old periglacial drainage network: the thalwegs may not have a continuous declivity, but can consist of a sequence of little slopes creating a series of discontinuities in the flow. Another problem comes from the DTM, whose 25 meters precision is unable to take into account gorges of small dimensions, which actually drain most of the basins. Moreover, the precision of one meter for the elevation data produces, in approximately flat areas, a large number of horizontal triangles in which the calculation of the vector of greater slope angle is not easy to calculate. When water flows over grass or cultivated area, the common mathematic models (such as Saint-Venant) is also not useful because laminar flow does not really exist (Langlois, 2007). Thus, the effects of gravity are computed with energy-based calculations, and velocity of flows does not directly depend on its mass:

$$\Gamma = kg \sin \alpha$$

with g the gravity influence (9.81m/s), k a constant factor and α the slope angle. The flow proportionally increases according to the time and the thickness quickly stabilizes flow speed in flat areas. The Saint-Venant equations indicate that flow speed (v) proportionally increases with water height, computing constant flowing (h, y) as a function of slope percent (θ) and discharge (Q). This idea can be obtained by the following formula:

$$v = \sqrt[3]{\frac{8gQ\theta}{f}}$$

$$h = \sqrt[3]{\frac{fQ^2}{8g\theta}}$$

with v the flow speed and h the water height (m). Therefore, the formula appears obvious since it derives from a model that calculates, at the same moment, the water height and it speeds according to a specific discharge. But in small and dry valleys, the discharges are not known in advance. Furthermore, the water height is weak (a few millimeters), slope gentle (a few degrees) and the friction force high face to water quantity. Then, we develop a linear model in which rules can be easily formalized. We define the v function (flow speed) with two variables (**fig. 2g**), in which h equals to the water height, and $u = sin\ \alpha$ the slope angle.

Six flow parameters are defined in RUICELLS (**fig. 2h**): the water height required to maintain a constant flow when the slope angle is negligible ($k_{00} = 1$); the water height needed for a constant flow if slopes are higher ($k_{01} = 0.1$); the water height threshold up to which flow speed attempts v_0 ($k_{10} = 50$) or v_1 ($k_{11} = 100$); the maximum speed if slope angles are negligible ($v_0 = 0.2$) or higher ($v_1 = 60$). All these parameters have been calibrated on the basin of Saint-Martin-de-Boscherville ($13.4 km^2$), partly by comparing with simulations results of the STREAM model (Merle, 2002) and partly by comparing with flow estimations derived from the maximum slack water deposits observed after the June 16th, 1997 flash flood event (Delahaye, 2002).

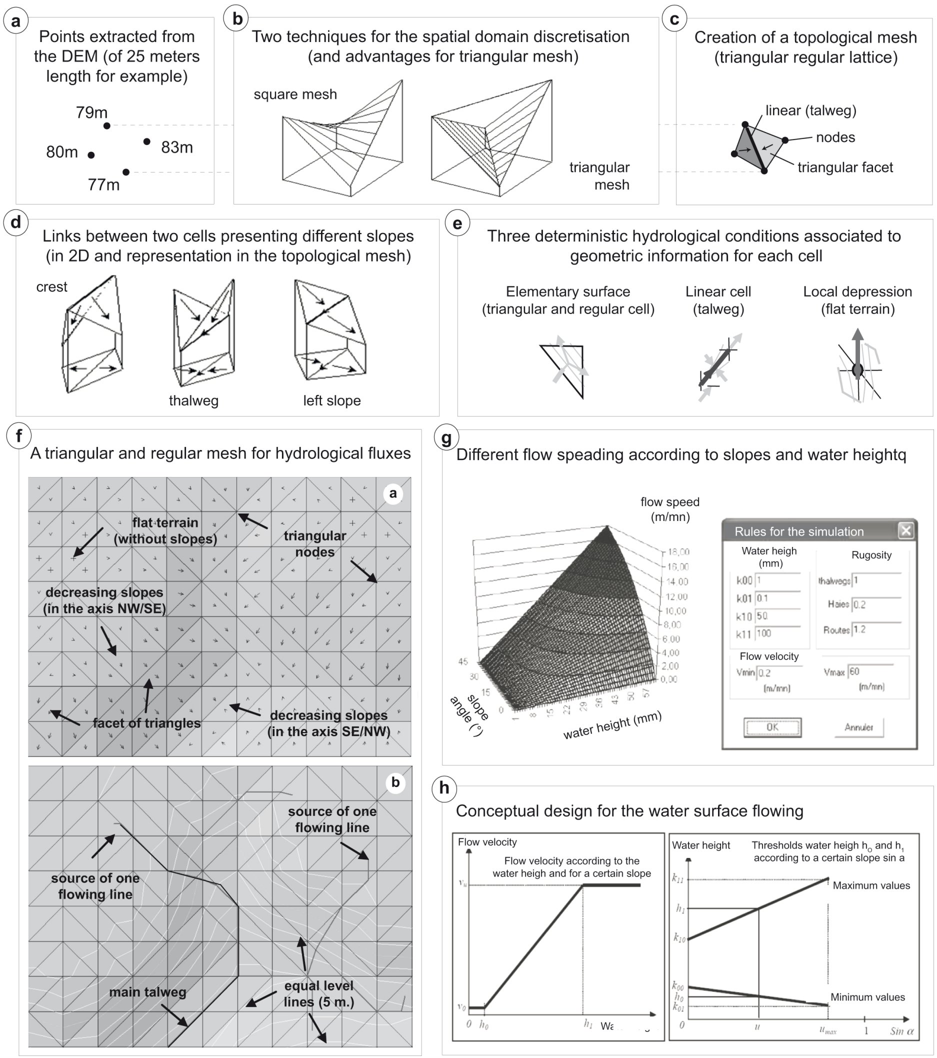

Fig. 2. Rules and main characteristics of RUICELLS (modified from Delahaye *et al*., 2001).

3.3. Data acquisition and chosen parameters

To simulate potential hydrological responses to various rainfall intensities, three types of input data are needed, aside from the DEM (source: IGN; resolution of 25 meters in this study): **(1)** a relevant Land Use Map (LUM); **(2)** water infiltration capacities; **(3)** the definition of rainfall intensities (with real data or not).

Two types of GIS-data were used to produce the LUM. The Corine Land Cover (CLC) permits to delineate real-world objects (lakes, cultivated fields, meadows, forests, industrial areas and natural areas). The CLC (with 46 hierarchical levels of classification) has been produced by the Agency of Development at the European scale and is derived from satellite images. By itself, this data is insufficient as it does not accurately delineate very small areas (< 0.05 km^2) and its precision is not enough to detect runoff sources. Therefore, we improved CLC (2006) using the Geographical Parcel-Based File (GPBF) (2010), created to help farmers apply for European Common Agriculture funding and kindly provided by the DREAL-Normandy service. This data (with 114 categories) enables us to precisely detail the dominant yearly type of land use (wheat, corn, flax, potatoes or others) for each season (spring and winter periods) over the last four years (2007-2010). GIS ground-truthing erased errors due to geometric intersections between CLC and GPBF. The new cross-combined data gives satisfying results as shown in the overview for the basin of Mesnil-Val (**fig. 3**). This basin (9.88km^2) has an elevation ranging from 26 m to 210 m over a distance of 1.1 km. Cretaceous calcareous rocks dominates its geology. Grasslands exist over the slopes exceeding 5 % in the middle parts of the basin and interact with springer peat, maize, sugar beet or wheat in downstream and upstream parts. A flash flood occurred on May 10th, 2000, and inundated the outlet (namely Mesnil-Val) and the village of Rainville (**fig. 3**). Although the LUM was mapped after the event (2000), it present few differences with the situation in 2000, i.e. the flood susceptibility remains high because land use does not change significantly in ten years (+ 3,2 % for cultivated areas, - 1,8 % for grasslands). The performance of CLC-GPBF is relevant for several reasons. Other data (earth observations or multi-spectral images) capture land cover at a given moment without allowing the assessment of the seasonality and of the evolution of agricultural practices, while surface states play a key role on runoff productions (Cerdan *et al.*, 2002). GPBF is available over the entire Seine-Maritime and permits a transferable method over the studied basins. The flash flood susceptibility conducted in this study is based on the most detailed and on the most recent data (2010), because simulations were launched in 2011. Nonetheless we shall update the LUM and compare the 2010 susceptibility assessment with those obtained for 2014 for example. Indeed, the ability to easily update the LUM and the implementation of GIS-data within the RUICELLS model are two major advantages of our study design.

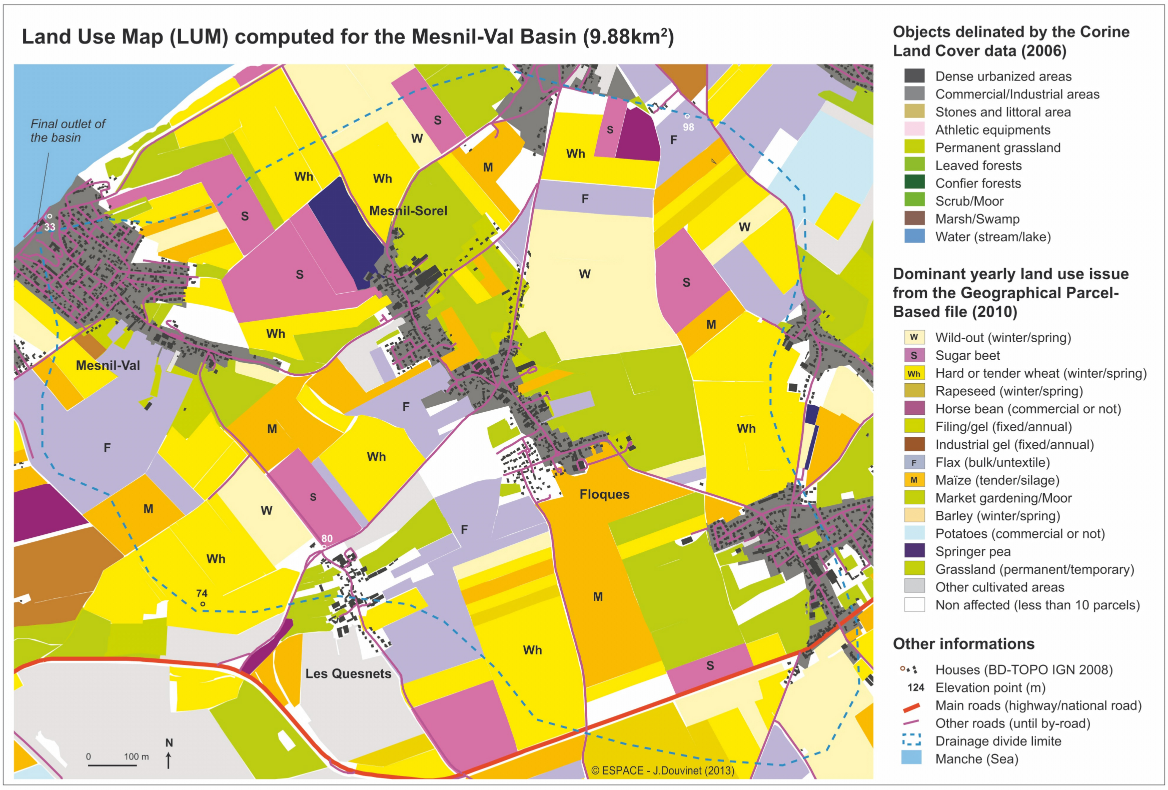

Fig. 3. Example Land Use Map (LUM), combining Corine Land Cover (CLC, 2006) and Geographical Parcel-Based File (GPBF, 2010), over the basin of Mesnil-Val (9.88km^2).

To associate water infiltration capacities with the LUM, we use the latter rather than runoff coefficients, for three reasons: **(1)** the infiltration capacities account for soil roughness, its sedimentology and the vegetation cover at one given moment (Cerdan *et al*., 2002); **(2)** runoff due to infiltration saturation, as per Horton's theory (1933), prevails during flash flood events (Kirkby, 2005); **(3)** the runoff coefficients give a minor role to cultivated areas and tend to underestimate runoff cumulative amounts (Douvinet, 2008). Previous research (Benkhadra, 1997; Lecomte, 1999; Joannon, 2004; Souchère *et al*, 2005) has been conducted over the entire Seine-Maritime to define infiltration capacities at larger scale. We use smallest infiltration capacities (**tab. 2**) to consider the worst-case scenario, where antecedent rains have saturated the soils and, consequently, water surface flows should occur in a few minutes. Even though these assumptions may not reflect the reality for a given storm event, the simulated flash flood susceptibility will alert forecasters and planners as soon as possible. The implemented coefficients are simplified for the main land use type and several data have been adjusted according to field-experiments conducted after previous severe flash floods (Delahaye, 2002). Sensitive cultivated areas in terms of runoff production play an important role: silage corn and sugar beet (3 $mm.h^{-1}$) have smaller infiltration capacities than potatoes (4 $mm.h^{-1}$) or winter wheat or rapeseed (5 $mm.h^{-1}$), whereas forest areas and permanent grasslands have higher capacities (50$mm.h^{-1}$). Initial rains have also been cut off (5 $mm.h^{-1}$) to account of soil porosity and vegetation imbibition. These assumptions can be criticized, because intensities at fine time-step (5 min.) strongly affect these factors (Cerdan *et al.*, 2002), whereas infiltration capacities used in this study never evolve during the modelling process. This point frequently poses a problem in numerous modelling approaches (Nearing *et al*., 2005). Nonetheless, the assumptions are retained here for simplicity and tractability.

Name of land use type in the CLC-GPBF database	AREHN (2005)	Cerdan et al., 2002	Delahaye, 2002	Joannon., 2004	Final parameters used in this study
Winter wheat	5 – 10	8 - 12	5	5 - 8	5
Silage corn	5 – 25	2 - 10	2	2 - 10	3
Winter barley	5 – 10	10 - 15	5	5 - 15	5
Spring barley	10 – 20	15 - 20	15	12 - 20	12
Rapeseed	5 – 10	8 - 12	5	5 - 12	5
Pea-grass	5 – 10	10 - 20	10	10 - 15	10
Flax	5 – 10	/	10	8 - 15	10
Production freeze	50	30 - 50	/	30 -50	30
Industrial freeze	5 – 10	/	5	5 - 10	5
Fodder	50	/	/	/	50
Temporary or permanent grass	50	/	50	50	50
Orchard	50	/	/	50	50
Sugar beet	2 – 5	2 - 8	2	2 - 8	3
Potatoes	2 – 5	2 - 8	2	4 - 12	4
Sunflower	/	15 - 20	/	/	15
Oil-producing	/	/	50	/	50
Seed areas	/	/	50	/	50

Tab. 2. Water infiltration capacities (in $mm.h^{-1}$) in Seine-Maritime, according to various studies, and minimal values chosen for the flash flood assessment in this study.

To account for rainfall variability, we assess the susceptibility of basins playing with different rainfall intensities. Two choices were possible: either we implement rains according to the frequency analysis methods for extremes, *i.e.* the SHYREG database (Renard *et al.*, 2013*),* or we consider project-rainfall scenarios for all basins. The first choice was not appropriate for this study for two reasons: **(1)** the statistic calculation of rains presenting small probability and large return periods introduce high uncertainties; **(2)** earlier research (Douvinet *et al*., 2009) underlined differences between measurements by official stations, radar and volunteer stations. For the storm event of July 25th, 2000, for example, Neuville-sur-Dieppe has officially measured 33.2 mm in 24h, whereas the radar pixelated 50 to 75mm in 2h (at a distance of 2km from the station), and a volunteer cumulated 78 mm in 1h15min. Thus, even if rains are not representative of the extreme possible events on each basin, we created a set of potential rainfall scenarios of different intensity and duration: 20, 30, 40 and 50 mm in 1h; 30, 40, 50 and 60 mm in 2h, 3h and 6h, Even though this flood susceptibility is likely overestimated in these worst-case scenarios, the highest intensities (50 mm in 1h) could locally happen.

3.4. Simulation set-up and outputs

Data are implemented as follows: **(1)** download the Digital Elevation Model in the RUICELLS model, which automatically converts it in a triangular and regular lattice (.mnt) and attributes hydrological roles to triangles, links and nodes; **(2)** the user identifies one or several outlet(s) - the basin limit is automatically calculated; **(3)** attributes of the Land Use Map (LUM), which is converted in a generate format in GIS (.gen), are exported and transferred on lattice, whereby a parcel covering up to 50% of one cell (25m * 25m) automatically defines it (similar geographical coordinates and GIS projection are required to avoid cartographic disturbances); **(4)** water infiltration capacities are linked to the LUM (.txt); **(5)** the user defines rainfall data (.txt). Following these steps, the simulations can be launched. At the end of the modelling process, the model outputs a graph that shows the evolution of discharges through time according to the rainfall input, and a map indicating the runoff amounts on each cell. An example is shown on the basin of Mesnil-Val **(fig. 4**). These simulations not only allow estimation of probable hydrological responses for a specific rain, but also the identification of spatial interactions between runoff production areas and points of measurement (Delahaye, 2002), at plot to basin scales, as well as a further understanding of important discharges and runoff amounts when rains exceed a critical intensity. For example, some basins may not respond gentle rainfall intensities, but produce high discharges after critical rainfall.

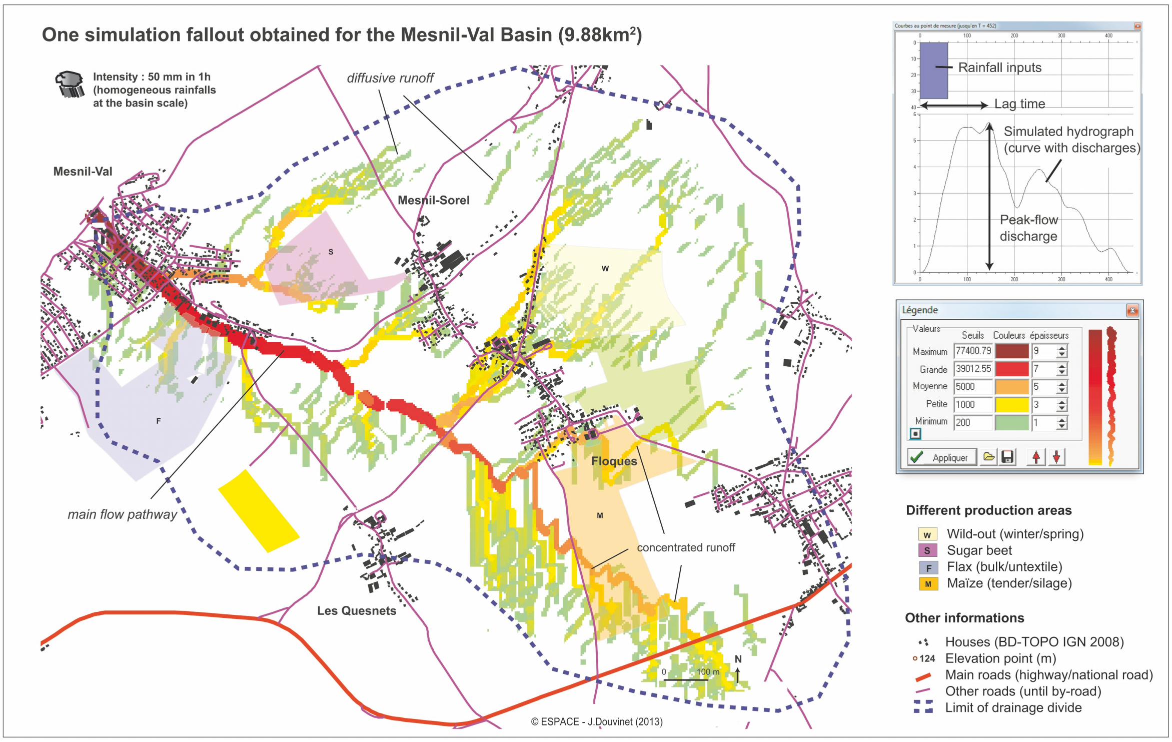

Fig. 4. One simulation fallout obtained on the basin of Mesnil-Val (9.88 km^2), permitting to simulate and to map the potential hydrological response for a storm event of 50 mm in 1 hour.

3.5. Limits for the modelling performance assessment

Normally, after a model is developed, it is tested before being put to use as a predictive or explanatory tool. This is a form of quality assurance and it involves the simulation of a situation for which observed data are available (Van de Wiel *et al.,* 2011). For this instance, the model parameters have been only calibrated for the 1997, June 16th event (Delahaye *et al*., 2001), through the simulation of the diffusion of the runoff process in two basins. The runoff map highlights the links between the contributing sub-basins and the successive concentrations in the basin and underlines all the areas most sensitive to the runoff processes. The divergence with the observations is important in the upstream southern part of the basin. The simulation, indeed, locates a major flow, that has not been observed in this area. The implements having not been integrated in the model, the simulation has not taken into account the influence of the highway crossing the upstream part of the basin. This highway stopped the flow and produced a flood leveling, generating retentions of water along many embankments. The observation shows the limits of the model, but stresses also the efficiency of such a tool to evaluate the incidence of an implement on the hydrological behaviour of a basin. On the other hand, these results show the accuracy of this approach and how, starting from a simple data set, it is possible to set up a cartographic presentation of the runoff dynamics. Simulations also give a good agreement in comparison with estimations proposed by more complex hydrological models (GR4J, STREAM and LISEM) and those derived from water deposits (Merle *et al*., 2001). Our simulations cannot be verified quantitatively due to a lack of independent data. Validation occurs only on a scenario basis and it is always possible to attribute errors of the simulations to inaccuracy of the initial or external forcing conditions, rather than to inaccuracy of the model's hypotheses (Van de Wiel et al., 2011). Even though Beguéria (2006) use for example confusion matrices to compare modelling and recorded events in true or false positives or negatives information (Kappes *et al*., 2012), the low availability of hydrological data of past events renders such approach impractical. Lacking an independent quantitative validation, these first modelling results are only evaluated in a qualitative way, which necessitates a careful interpretation (see section 5.1).

4. Results and susceptibility assessment

Simulations are analyzed for three main variables that characterize basin susceptibility of flash flooding: peak-flow discharge (Q), peak unit discharge (Q_s), calculated by dividing Q by the basin size, and lag time (T), *i.e.* the duration between the beginning of rainfall and the onset of peak discharge (and not the time between the onset of peak rainfall and the onset of peak discharge, due to the simulation configuration), for each of the 148 studied basins and each of the 16 rainfall intensities. Even though results are available on each basin, they are presented here in aggregated form, *i.e.* at large scale, to facilitate the susceptibility analysis.

4.1. Peak-flow discharges

The model allows identifying that the number of susceptible basins strongly increases with rainfall intensity. In the following analysis, we use three arbitrarily chosen peak discharge thresholds to identify small (from 4 to 7 m^3/s), medium (from 7 to 10 m^3/s) and high (> 10 m^3/s) susceptibilities to flash flooding (**tab. 3**). For events with 30 mm of rainfall in 1 hour, 13 basins have peak-flows with Q > $4m^3/s$ (**fig. 5a**) but only one exceeds 7 m^3/s (Val-de-Saâne). At 40 mm in 1 hour, 70 basins have Q > $4m^3/s$ (**fig. 5b**), 17 of which have Q > 7 m^3/s and 3 have Q > $10m^3/s$ (Val-de-Saâne, Lézarde amont and Val-aux-Scènes). At 50 mm in 1 hour 72 % of the studied basins (104 out of 148 basins) have a Q > $4m^3/s$, 56 of which have Q > 7 m^3/s and 21 have Q > 10 m^3/s (**fig. 5c**).

Similarly, the susceptibility decreases for rainfalls more spread over time. For example, for storm with 50 mm in 2 hours, only 33 basins have Q > $4m^3/s$ (**fig. 5d**) and 6 basins have values up to 7 m^3/s. In terms of land use, susceptibility to flash flooding is higher in basins where percentages of sugar beet, corn, maize and flax are important. These basins are subject to flash flooding at 30 mm in 1 hour, and even react to lower intensity storm events of longer duration (e.g. 40 mm in 2 hours or 50 mm in 3 hours). Conversely, the peaks of discharges of other basins, in which cultivated areas are more dispersed, suddenly increase (> 7 m^3/s) for more intense storm event of 50 mm in 1 hour. Grasslands are sufficient to reduce the runoff production coming from upstream parts for gentle rainfall intensities (< $40mm.h^{-1}$), but become inefficient for more intense rains. Basins with other dominant land use present intermediary behaviours between these extremes.

At larger scales, several basins with high responses are spatially concentrated, especially along the coastal areas along The Channel, the Seine River or along a few tributaries (Scie, Durdent or Saâne rivers). In this case, several floods can tumble down the dry valleys at the same moment, which can generate high-risk levels in case of an extended thunderstorm (> 10 km^2). Flash floods from similar events, but occurring over more isolated basins (such as in the eastern part of the department), are easier to manage and to prevent. In a qualitative way, the comparison with historic flash floods occurrences (over the period 1983-2005) shows a good correlation with the highest Q values: the three basins identified as the most susceptible in our simulations for storm events of 40 mm in 1 hour, also have historically observed flood events). However, the validations are not systematic. For example, flood events have been observed in 12 of the 21 basins identified, as the most sensitive for 50 mm in 1 hour, while the results for 30 mm in 1 hour, as well as for 50 mm in 2 hours, are a less successful indicator. Therefore, the Q values need to be divided by the basin size, since weak peak-flow discharges do not have the same hydrological significance in small and large basins.

4.2. Peak unit discharges

Previous studies carried out on Mediterranean floods (Carrera *et al.,* 2007; Gaume *et al.,* 2009) highlighted that surface flows become strongly erosive when peak unit discharges (Q_s) exceed at least $0.7m^3/s/km^2$. An earlier study (Douvinet and Delahaye, 2010), carried out a few days after several flash floods on five areas in northern France, permitted to estimate a threshold of 1 $m^3/s/km^2$ for minor erosion forms and of 1.5 $m^3/s/km^2$ for major incisions on soils (gullies) or roads (destruction of network infrastructure). Thus, the analysis of simulated Q_s takes into account these thresholds (**tab. 4)**. Occurrence of peak unit discharges strongly increases with rainfall intensity. For storm events with 30 mm in 1 hour, only 7 basins have Q_s > $1m^3/s/km^2$; at 40 mm in 1 hour, 26 basins present Q_s exceeding this threshold (**fig. 6a**), whereas 64 basins do so at 50 mm in 1 hour (**fig. 6b**).

Clear trends are observable, with especially high Q_s values along several humid valleys (Durdent, Valmont and Bolbec) and with the highest peak unit discharges occurring in the smallest basins. The basin size increases more quickly than Q and this explains why high Q_s values are rarely observable on "larger" basins (ranging from 10 to 20 km^2). Even with the provision that these first modelling results need to be treated with care, three points are important: **1)** small basins can produce high Q_s values, independently of their land use, and rainfall-discharge models are insufficient to manage their susceptibility; **2)** basins combining large basin area (> 10 km^2) and a Q_s value greater than 1 $m^3/s/km^2$ are the most sensitive since they can produce the most damaging floods; **3)** concentrated high Q_s values induce high risk in several valleys (Lézarde, Valmont). In a qualitative way, the comparison with historic flash floods occurrences (over the period 1983-2005) shows a good relation with the highest Qs values (5 of the 9 basins identified as the most sensitive in our simulations for storm events of 40 mm in 1 hour, and 17 of the 34 basins for 50 mm of rainfall in 1 hour, had historic events).

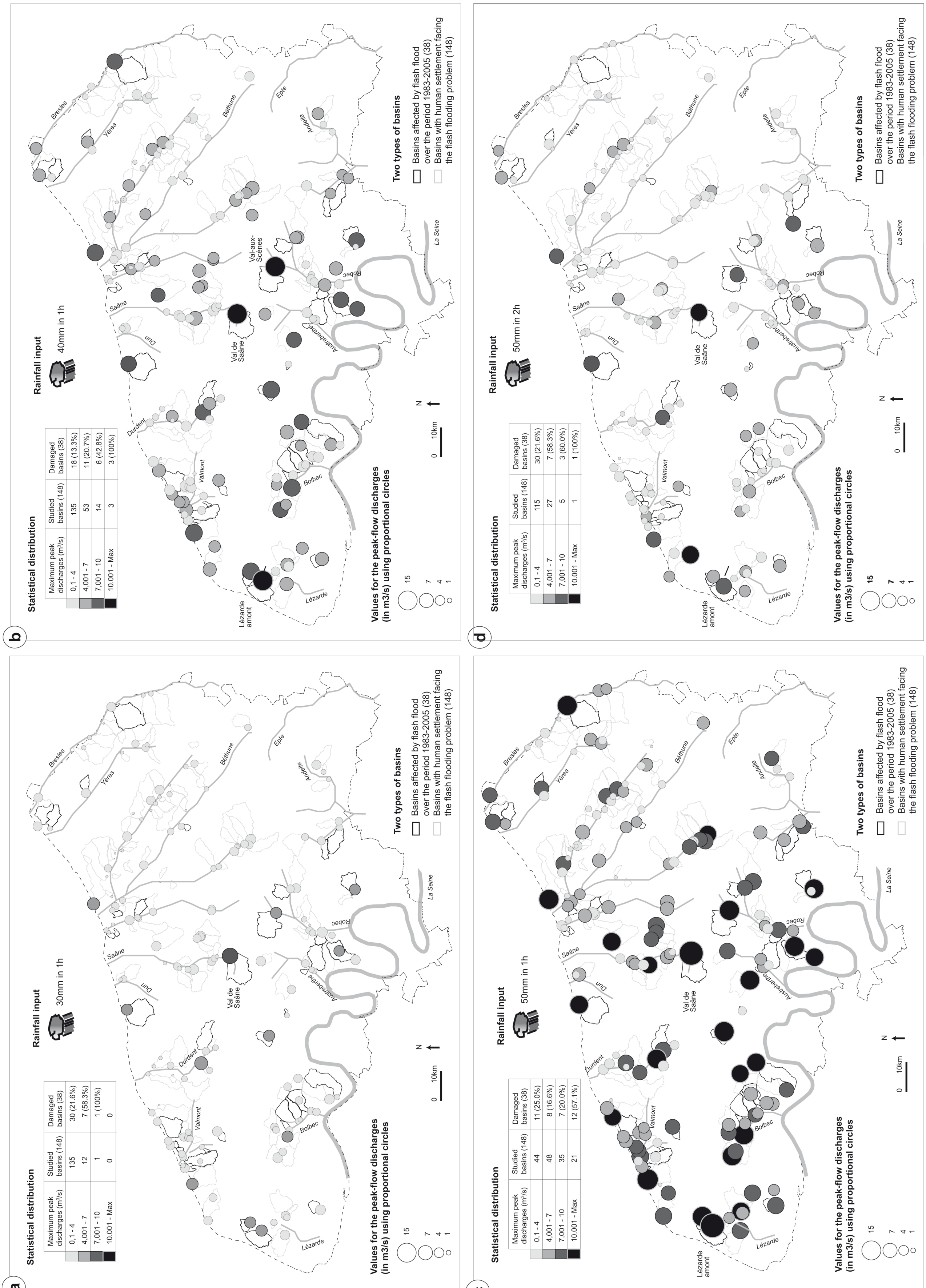

Fig. 5. Evolution of the peak flow discharges simulated by RUICELLS over the 148 studied basins, according to different intensities varying from 30 mm **(a)**, 40 mm **(b)** and 50 mm **(c)** in 1 hour to 50 mm in 2 hours **(d)**.

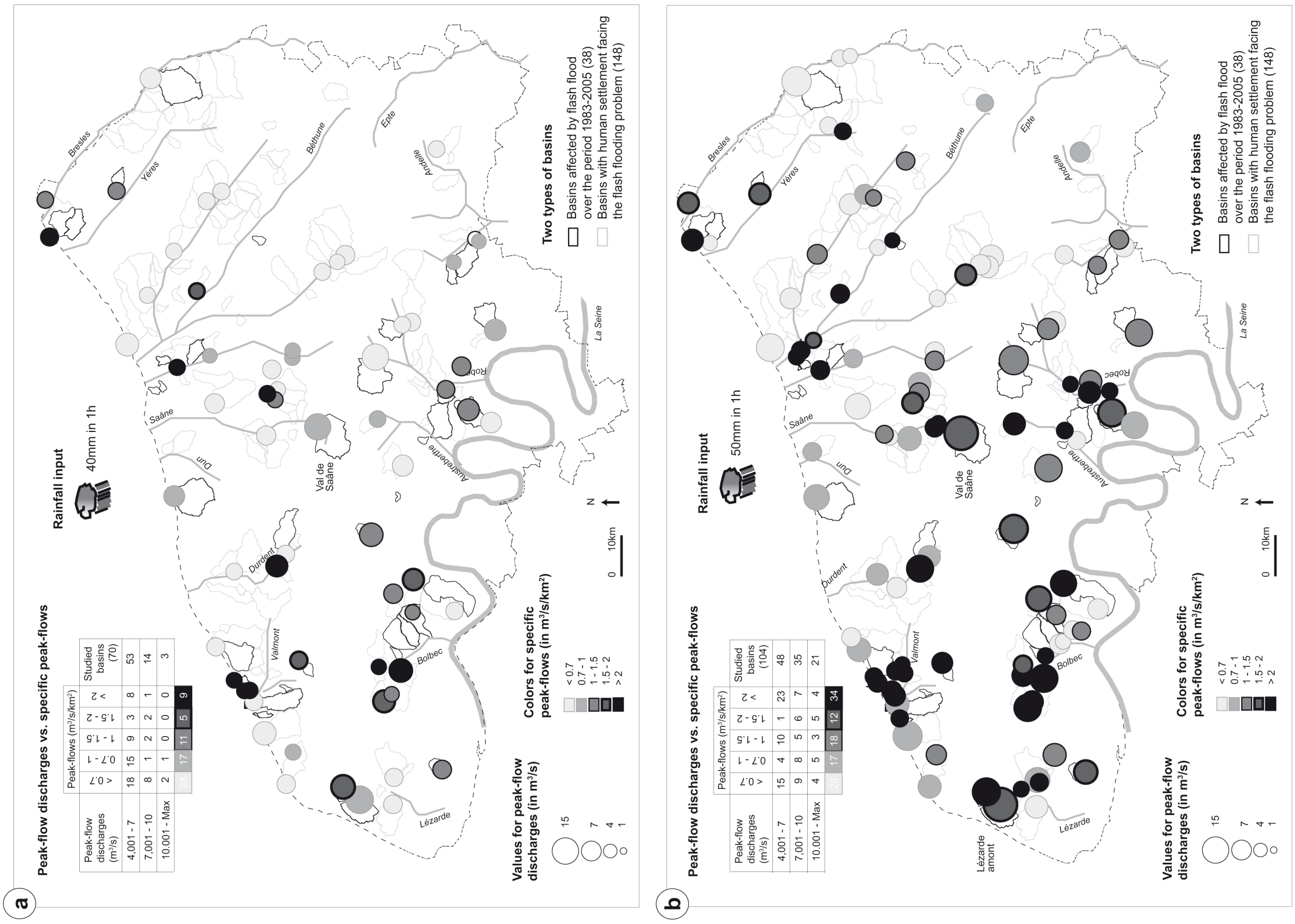

Fig. 6. Evolution of the peak unit discharges simulated by RUICELLS over the most sensitive basins (with peak discharges > 4m^3/s) for storm events of 40 mm **(a)** and 50 mm **(b)** in 1 hour.

4.3. Lag times

An important question facing the flood forecasters concerns the time they can have to alert the local authorities and the population for evacuation or for protection in areas at risk. The French Ministry of Environment and the General Delegation on Majors Risks (DGPR, 2011) focus on this point after dramatic flash floods occurred in the western coastal part of France (49 deaths in February 2010) as well as in the southern part (25 fatalities in June 2010). To address this question, lag time, *i.e.* the time separating the beginning of rains and the occurrence of peak-flow discharge, was computed. Hydrologically, this differs from the time of concentration but it equals the duration of increasing flow (*i.e.* the rising limb of an hydrograph). The modelling results underline an increasing number of basins with short lag times as rainfall intensity increases (**tab. 5**). 11 basins responding 40 mm in 1 hour (**fig. 6a**) present short lag times (*i.e.* in less than 2 hours) and only one of these (the Hanouard basin) has high Q, high Q_s and short T. In contrast, 42 basins showing susceptibility for events with 50 mm of rainfall in 1 hour, and cumulating discharges up to 4m^3/s (**fig. 6b**), have lag times less than 3 hours, 22 of which have lag times less than 2 hours.

Several basins with peak-flows ranging from 4 to 7 m^3/s present the smallest lag times. The forecasters need to pay attention a greater attention on these as they can simultaneously produce several flash floods. Fortunately, all these identified basins very unlikely generate high flows at the same moment, since a storm event with 50 mm of rainfall in 1 hour is very unlikely occur over the entire Seine-Maritime. However, such storms can threaten this area in the future (following the predictive scenario 2.a; GIEC, 2009) and can affect multiple basins locally if they are within close proximity. On the other basins, lag time increases with basin size, and forecasters should have more time (> 3 hours) for alert. In a qualitative way, the comparison with historic flash floods occurrences (over the period 1983-2005) show bad correlations (whatever the rainfall intensities) because only a few number of basins with historical floods present small lag times. Hence, this parameter is of paramount importance for forecasters, but seems to be the less useful to explain the flash flooding susceptibility.

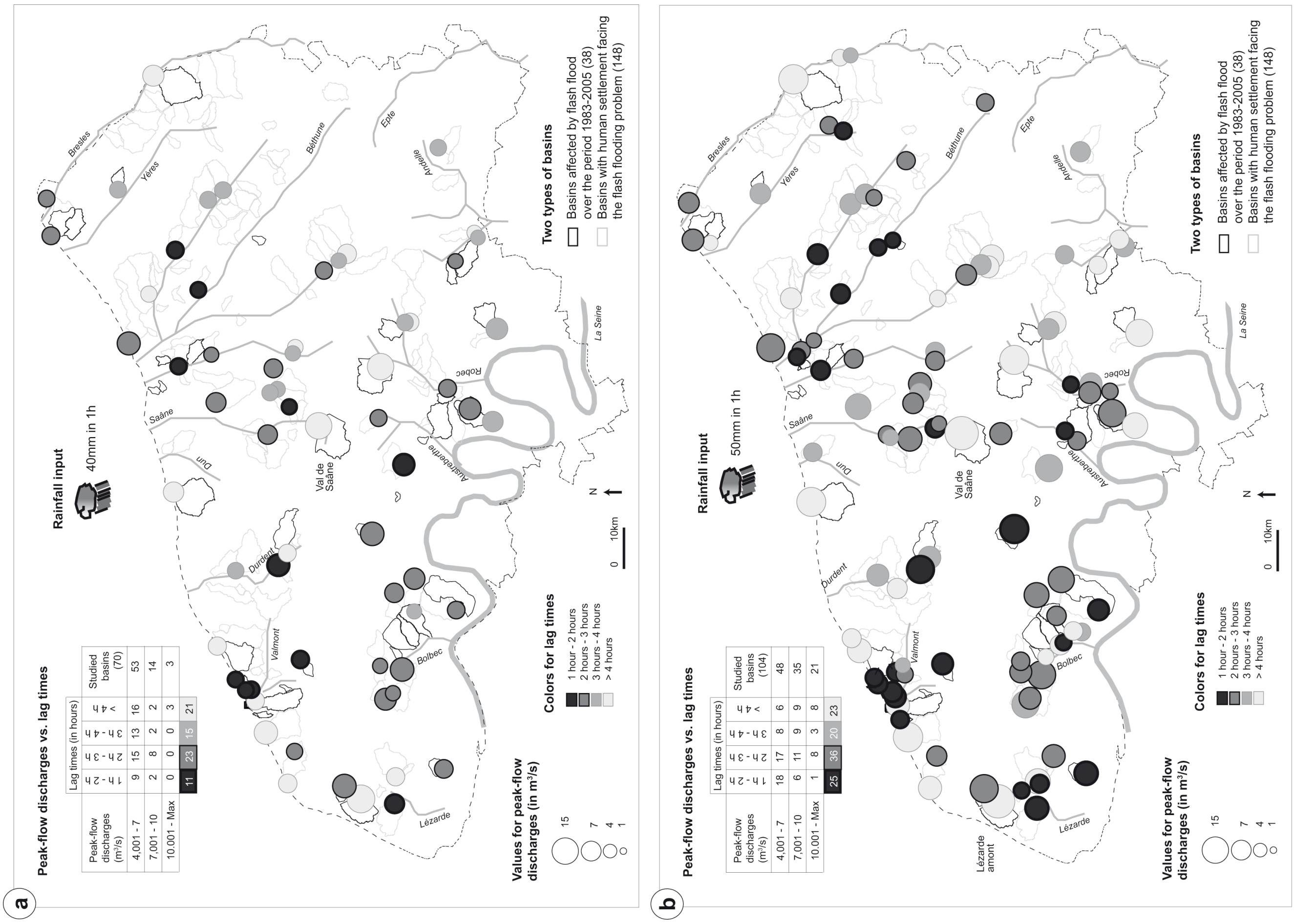

Fig. 7. Evolution of the lag times simulated by RUICELLS over the most sensitive basins (with peak discharges $> 4m^3/s$) for storm events of 40 mm (**a**) and 50 mm (**b**) in 1 hour.

5. Discussion

5.1. Validation efforts and limits

The modelling validation is a fundamental step because this determines both the quality of the approach and the credibility of simulation results. In this study, this process remains difficult due to the relatively low number of basins (38) affected by previous flash flood events (over the period 1983-2005). If we focus on the simulations obtained on these 38 basins, 17 (46%) have peak unit discharges up to $0.7\ m^3.s^{-1}.km^{-2}$ and 24 (63%) have a peak flow discharge up to $4\ m^3.s^{-1}$, for a rain of 50 mm in 1h. Even if these results indicate that the model is successful in identifying flash flooding in most of these basins, it means that a number of basins where historical flooding was observed did not experience flooding in simulations (14 out of 38, or 37%). On one hand, the identification of such differences can be explained by three arguments: 1) the real rains were more intense than our maximum intensity rainfall scenario (50 mm in 1h) - by running simulations with higher intensities (i.e. from 60 to 100mm in 1h), we observe that all the 38 basins present high sensitivities for a rain up to 78 mm in 1h; 2) a higher sensitivity to runoff and flash floods (even though the peak unit discharge does not exceed $0.7m^3.s^{-1}.km^{-2}$) because of a strong human settlement in the outlets - this hypothesis is attested on 9 basins out of the 14 studied; 3) the simulations underestimate the impact of the "built" environnement' in LUM. On the other hand, how can we explain the identification of other basins for which the simulations indicate flash flood susceptibility, but where no historical observations are present? If we trust in local observations on "non-affected" basins, provided by stakeholders or risk managers, 35 basins (32%) known local problems (inundated depressions, small erosions) after intense rains. If we consider this *verbatim* as validation tools, the flash flood susceptibility is confirmed on 59 basins (57% of the 148 studied basins). Finally, if the critical rain is recorded in the future, we should survey the basin reactivity and then see if the simulation results can be validated *a posteriori*.

The model's success in identifying flash flooding over a majority of basins where historical flooding indeed was observed indicates that it can be used to anticipate flash floods in the Seine-Maritime. However, since the simulations cannot be completely validated, care must be taken in interpreting the results.

5.2. Advantages and limitations for anticipation

Anticipation of flash floods in small basins becomes urgent, since they induce rare, violent and sudden impacts on inhabited outlets. Furthermore, the local population is unaware of the possible flash flooding risk to which they are exposed. The other models developed earlier, such as STREAM, LISEM or WATEM (De Vente and Poesen, 2005; Nearing *et al.,* 2005), permit to manage flash flooding susceptibility for a specific basin but not on many basins, since local to outlet scales, and by playing with different intensities. Therefore, these simulations proposed by RUICELLS can improve our knowledge without taking into account rains frequency. This approach consists of combining the most recent and available GIS-data with the CA modelling. Results are discussed with local stakeholders and risk managers to verify whether the highest simulated susceptibilities have resulted in previous problems. Simulations obtained in many basins are not validated but several experimentations in real time should be planned over the next ten years. Nonetheless, these preliminary investigations give promising results. We hope that this kind of work will serve not only to help farmers reducing soil losses, but also to help forecasters to define places or roads where potential high-level damage can be expected. There is a need to protect people if time to react does not exceed a few minutes, as it was the case in the basin of Saint-Martin. We could also diffuse a vigilance signal with colors ranging from green to red, as it already exists in France for floods over greater basins (www.vigicrues.fr).

Similar investigations may be carried out in other sedimentary areas where the flash floods also occurred with violence in the last years, such as in Sussex (Boardman, 2004) and in Flanders (Evrard *et al.,* 2007). On the other hand, these maps also question the networks capacities and the socio-economic stakes to face to flash flood events, and they also necessitate the study of resilience of societies and the evaluation of economic losses (Douvinet *et al.,* 2013). For this, we have to quantify the precise structural vulnerability to flash floods at the inhabited outlets, and the time needed for the restoration post-event. We will work on it with the SCHAPI (the French forecasting official service) over the period 2013-2016).

6. Conclusion

The anticipation of flash floods in small and dry basins located in the Seine-Maritime is hampered by a lack of hydrological, meteorological and geomorphological knowledge. The rareness and violence of such events make the measurement of hydrological responses and behavior after intense rains difficult. In this paper, we present the methodological investigations and the flash flooding susceptibility results obtained on the entire department of Seine-Maritime using the CA RUICELLS model. We rely on the hydrological estimations (peak discharges, specific peak discharges and lag time) and the critical rains to identify conditions, at local scales, which may necessitate increasing vigilance from hydrological and meteorological forecasters (like for the FFG, *Flash Flood Guidances,* created in USA, Estupina-Borell *et al.,* 2005). We emphasize the need for a careful interpretation of simulation results, remaining conscious of inherent assumptions of the model used and of the quality of input data. Even though the information on a number of documented flash flood events exist (Douvinet, 2008), records for some susceptible areas are missing, which impedes the validation of a deterministic modelling approach, as adopted in this study. However, validations efforts could provide levels at which to issue alerts and question the potential effectiveness of a specific flash flood alert system for this region. And for this, field-experiments and surveys are expected during the next two years.

Two main questions should be addressed in these subsequent studies. First, these floods are associated with high sediment concentrations that remain difficult to define. Indeed, managers and official services clean the flooded urbanized areas and erase deposits before they can be surveyed and studied. Thus, even though sediment sources are well known (soil erosion, destabilization of slopes and mass movements, incision in road networks, overthrusting of debris, vegetal and artificial elements adding to solid fluxes), a precise quantification of the sediment budget is an insolvable problem in these small and ungauged areas (Douvinet *et al.,* 2013). Second, the lack of knowledge on specific stream powers (measured only in a few cross sections) and on influential factors (links between land use, morphological features and rainfall intensities) for flash flooding requires additional studies. Indeed, a better assessment of the minimum values needed to induce erosion, incision and flash flood should help us for a further understanding of the emergence of a turbid wave observed in several thalwegs.

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